Display's the Thing: The Real Stakes in the Conflict over High-Resolution Displays

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Abstract

Japan has a strong lead over both the United States and Western Europe in the development of liquid crystal displays (LCDs). We argue in this article that LCDs and associated integrated display technologies are critical for competition in a growing proportion of global electronics markets. The "architecture of supply" is the issue here, and U.S. firms need help from the government to insure that they will have access to the latest display technologies in a timely manner at market prices. Besides adopting foreign economic policies designed to achieve this purpose, it will be necessary for the government to continue to work with the domestic electronics industry to raise the industry's technological capabilities in new display technologies.

INTRODUCTION

In Akira Kurasawa's film *Rashomon*, several witnesses to a murder tell the story of what they saw. Despite viewing the same event, the witnesses' stories are so radically different that the event itself is ultimately called into question. So has it been with the debate over the next generation of high-resolution video technology. Some see a bigger and better television set (HDTV), but usually dismiss what they see as economically (though perhaps not politically) insignificant.[1] Others see a significant component technology (high-resolution displays or HRD) beginning to pervade a wide variety of electronic systems. They recognize in displays a technological kinship to silicon chips—an industry with potential strategic significance for commercial and military applications.

But the conflict of perspectives should not, as it did in Rashomon, cast doubt on the event. The high-resolution display industry is a symbol of a

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[1] For them, a TV set, a desk set, and a set of luggage are economically indistinguishable: Each affords approximately the same possibility for economic growth; if the economy does not produce one, it will produce another.

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major transformation underway in electronics: that is, the emergence of new component, machinery, and materials technologies driven by commercial, high-volume, integrated microsystems applications. The industry's transformation is fundamentally altering the sourcing, development, production, and integration of electronics technologies and systems, and in the process is creating new patterns of industrial constraint and opportunity, with significant economic and military implications for the United States.

The Architecture of Supply

Should we be concerned about the shifts in the sourcing and production of electronics technology and know-how? Don't technologies and the capabilities they embody diffuse rapidly across national boarders in a relatively open world economy? If diffusion were perfect and instantaneous, then there would be little cause for worry. But, of course, diffusion is not perfect because not all relevant know-how is internationally accessible through market and nonmarket mechanisms. Nor is diffusion instantaneous, since the ability to absorb new capabilities depends in part on the available mix of old capabilities. Technology diffusion, like technology development, is a path-dependent process of learning in which today's ability to exploit technology grows out of yesterday's experience and practices. For example, because the demise of the American consumer electronics industry brought with it a sharp decline in corresponding skills, there is today little U.S. capability to competitively produce liquid crystal displays (LCDs) in high volume—*even though the basic technology is internationally available.*

Or consider the task of fully integrating a new Nikon stepper (a specific kind of semiconductor manufacturing equipment) into an existing fabrication line. The machine can be bought in Japan. Not all of the relevant know-how is embodied in the machine. On-site vendor-supplied technical support is essential to timely and cost-effective integration. Nikon's capacity and willingness to supply that support is much greater in Japan, where most of its engineering resources are located, than in the United States. A U.S.-based firm has far less ability than a Japanese-based counterpart to absorb the new technology in a timely fashion and at low cost—even though it is available on the market—because existing domestic capabilities are different (i.e., the domestic economy lacks Nikon's accumulated know-how).

The speed and degree to which technical know-how flows across national boundaries thus depends crucially upon the character of local capabilities. In the United States, for example, markets are open, employee mobility is very high, firms can be purchased outright, and short-term capital market constraints often push firms to license proprietary technologies. In general, U.S. technology accrues locally but diffuses rapidly even across national boundaries. By contrast, in a country like Japan or Korea, markets are less open, skilled labor mobility is low, acquisitions are virtually impossible, patient capital is available, and relevant networks (i.e., the supplier network in the Nikon example above) and national institutions are extremely difficult to access. As a result, considerable accrued technological know-how is retained locally in Japan or Korea and never diffuses as readily or rapidly across national boundaries.

In other words, successful diffusion of technologies from one economy to another is not automatic even in an open world economy. It depends upon whether or not the relevant capabilities are effectively accessible in the locations in which they reside. In this context, "effective access" exists when technological capabilities are available in the required amount and quality, in a timely fashion, and at a competitive cost. Conversely, the capabilities are not effectively accessible when unavailable at the appropriate quantity, quality, timing, and price.

As electronics pervades the modern economy, industrial innovation depends centrally on the component, materials, machinery, and control technologies (i.e., software in digital electronics) that are combined to create new products and processes. Effective access for a domestic economy to those technological capabilities is a function of the available "supply base" or, to use a spatial metaphor, the "architecture of supply." By architecture of supply we mean the structure of the markets and of other organized interactions through which component, materials, and equipment technologies reach producers.[2]

The supply base affects producers in two ways. First, different architectures of supply can either *enable* or *deter* access to appropriate technologies in a timely fashion at a reasonable price. Second, different architectures of supply imply different opportunities to engage in the interaction and support (between suppliers and producers) that are necessary to effectively exploit the technologies that are accessible. These points are worth a closer look.

The architecture of supply helps to structure technology access, timeliness to market, cost, and opportunities for interaction between suppliers and producers. To see how, consider a supply architecture in which suppliers of all relevant components, machinery, and materials are domestically based and all production capabilities local. Let us say that the suppliers are numerous and highly competitive. They interact with their customers through arms-length transactions in markets that are cleared by prices, and have the local capability to provide high levels of service and support on demand. They do not compete with their customers, and have no other strategic imperative then to make their products (i.e., machinery, components, materials) available to as wide a customer base as possible.

This kind of supply architecture would ensure domestic producers easy access through the market to all relevant technologies in a timely fashion and at reasonable cost. Moreover, it offers extensive opportunities for suppliers and producers to interact effectively. Since all relevant production and interaction is local with this supply architecture, the domestic economy is supported by a fully capable supply infrastructure. Technological learning cumulates indigenously. Technological spillovers and other external economies accrue locally to the benefit of the domestic economy. In fact, this architecture describes quite accurately both the electronics supply base of the U.S. economy through the mid-1970s and the economic benefits that accrued to the U.S. economy as a result.

Now consider a different kind of supply architecture, one in which domestic producers are dependent on international markets for supply of technology, markets which, in this scenario, are relatively closed to trade and investment. These markets are also simultaneously oligopolistic and geographically con-

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[2] The supply architecture idea originated in the work of Michael Borrus. For an extended discussion, see Borrus [in press]. Related notions, though developed very differently, can be found in the work of Moran [1990], Carlsson and Jacobsson [1991], and Anderson [1992].

centrated. Moreover, the few major suppliers compete directly with their customers—that is, they supply components, but also produce the electronic systems that incorporate the components. In this case, most of the relevant supplier know-how is geographically concentrated. Opportunities for support and learning by interaction are available only to customers with a significant local presence in the supplier's heartland, and on terms largely dictated by the supplier.

This kind of architecture permits suppliers great strategic leverage. They have the ability to exercise market power or to act in concert to control technology flows. They can begin to dictate access to relevant technologies, the speed with which their customers can incorporate the technologies into new products, and the price the customers pay for the privilege. The suppliers can set the level of support and interaction with customers to emphasize their own learning rather than that of their customers. Such strategic leverage can have irreversible, long-term consequences. For example, it can result in subtle pressures that delay a customer's new product introduction. Studies estimate that a new electronics product that is only 6 months late to market may sacrifice up to one third of its potential revenue stream.[3] Reduced revenues retard R&D, further delaying new products, and initiate a competitive downward spiral. Indeed, the nature of this supply base—characterized by oligopoly, economies of scale and learning, first-mover advantages, and the potential to dictate downward spirals to competitors—tempts established suppliers to engage in predatory policies and practices to preserve their leverage.[4]

This kind of supply architecture would significantly constrain producers abroad who were dependent on it, and would have great potential to eliminate opportunities for the dependent foreign economy to capture spillovers and other externalities. From the perspective of the distant economy, most of the relevant production activities lie abroad, as do all of the leading-edge activities that generate most of the spillovers. The pace of domestic technical progress—the ability to exploit the machinery, materials, and component technologies that underlie all electronics—is effectively controlled from outside the domestic economy.

High-Volume Electronics

Supply architectures are not static, they evolve dynamically through the force of market competition (and sometimes, government intervention). The supply architecture in electronics for key component technologies may well be moving from its historic openness toward restriction. Such a move would pose real constraints for some firms and could significantly limit their ability to effectively pursue new opportunities in both commercial and military electronics.[5] The shift in supply architecture is being driven by a new competitive dynamic in the market for final electronic systems.

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[3] Based on data developed in Reinertsen [1983]; see also Stalk and Hout [1990].

[4] In particular, subsidized, sunk investment by the oligopolists creates overcapacity and raises huge barriers to new entry, thereby preserving the supply base for those who control it.

[5] As suggested below, through creative strategies the very largest multinational firms are often able to overcome many—though usually not all—of the constraints inherent in a particular supply architecture. By contrast, small- and medium-sized firms are much more constrained by the existing architecture, and more dependent on national channels of technology flow.

Competitive developments in electronics systems are normally analyzed according to the markets for their application—consumer, computers and data processing, office automation, telecommunications, industrial, professional, and military. Today, however, the aggregate market data actually disguise an underlying dynamic: Products whose markets are growing the fastest, though they appear diverse by conventional categories, actually share many of the same specific technologies. Consider the following product set for instance: laptop, notebook, and hand-held computers; optical-disk mass storage systems; smartcards; portable faxes, copiers, printers, and electronic datebooks; portable and cellular telephones and pagers; camcorders; electronic still cameras; compact disc players; hand-held televisions; controllers for machine tools, robots, and other industrial machinery; engine, transmission, and suspension controls; navigation; and automotive systems like those for anti-skid braking.

These products are miniaturized systems built around embedded, often dedicated, microprocessors (or microcontrollers) with embedded software for control and applications. They are multifunctional, combining computing functionality with communications, consumer functionality with office functionality, and so on. By virtue of their size, such products are increasingly portable. They are also networkable; that is, their capabilities are significantly enhanced by being networked together into larger information systems.

The most distinctive characteristic of these products, however, is that they comprise sophisticated, industrially significant technologies that are manufactured in volumes and at costs traditionally associated with consumer demand. Taken together, these products define a new electronics-industry segment in which Japanese firms appear to have a leadership position—high-volume electronics. The emergence of high-volume electronics has two significant implications.

First, because development costs for the underlying component, materials, and machinery technologies are spread across mass market volumes, the new product segment can support the development of new technologies that used to be supported only through military spending, other public subsidy, or monopoly profits. Second, to meet consumer-like price points, the underlying technologies must be pushed to the lowest possible production cost levels without sacrificing high-performance functionality, quality, or reliability (an electronic component for engine control, for example, is a highly complex device that must not fail in operation). The overall result is that high-volume electronics is beginning to drive the development, costs, quality, and manufacture of leading-edge technological inputs critical to all electronics, including military. At stake is a breathtaking range of essential technologies from semiconductors and storage devices to packaging, optics, interfaces, machinery, and materials. As the next section suggests, nowhere are these implications clearer than in the case of high-resolution displays.

HIGH-RESOLUTION DISPLAYS AND SYSTEMS

Advanced displays (the core technology) and *integrated display systems* (i.e., electronics systems integrated with the core technology) will provide strategic leverage to shape competitive outcomes in future electronics markets. Advanced displays will contribute a sizable and perhaps increasing portion of the total value-added of electronic systems. As the first full-color LCD notebooks suggest, displays will be used competitively to differentiate products.

There will be extensive integration of advanced displays with other component technologies to create cheaper, more portable, and more user-friendly information-processing products. Integrated display systems will require the development or refinement of technologies used in almost every branch of electronics—lithography, etching, deposition, bonding, packaging, testing, and so forth. Those who manufacture both displays and high-volume systems will increasingly shape the most important underlying technologies. In short, control over display technologies will become almost as important in future electronics markets as control over integrated-circuit technology has been for the last three decades.

Advanced Displays and Integrated Display Systems

An advanced display is one that allows the display of large amounts of information over a wide range of image sizes. For this reason, advanced displays are sometimes called "high-information-content displays." When the information to be displayed involves full-color images, then the greater the brightness, contrast, and accuracy of the colors in the image, the better the display. When the information includes animation or real-time video, the speed with which frames can be displayed and the degree of dynamic resolution (absence of blurs caused by motion of the images) are measures of the sophistication of the display.

One way of thinking about advanced displays is in terms of pixels and bits per pixel. A pixel (short for *picture element*) is the smallest addressable part of a display. In monochrome displays, each pixel is a dot that can be on or off, or some shade of gray.[6] In color displays, it is generally necessary to combine red, green, and blue (and sometimes white) dots in clusters to get the desired color for an individual pixel [Mentley, Castellano, and Blanchard, 1990, p. 30]. The more pixels a display has, the more information it can convey. The more variation in brightness that is possible at each dot, the more information the display can convey.

At the moment, the architecture of supply for displays is relatively open because cathode ray tube (CRT) technology, the still-dominant display technology, is supplied by numerous highly competitive firms all over the world. New technology, controlled by many fewer companies, principally in Japan, is gradually displacing the CRT. Through the 1980s, however, the overwhelming majority of displays were still based on variants of the cathode ray tube. Televisions have been the main source of demand for CRTs, although in the last decade CRTs have been increasingly used in computer monitors.

CRT technology has developed incrementally since the 1930s, moving from monochrome to color, from lower to higher resolution, from rounded to rectangular and flat display surfaces. Current research on CRTs is oriented toward making the display surface larger while also reducing its overall bulk. Almost all current projection televisions use three CRTs (one each for red, green,

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[6] In monochrome displays with grey-scaling, the dot may be clear, opaque, or some intermediate degree of opacity. Henceforth, when we refer to a dot being switched on or off, we do not exclude the possibility of the dot being some shade of grey.

and blue colors) together with optical devices to project images onto flat screens. The invention of CRT-projection systems has led to the adoption of a terminological distinction between direct-view and projection displays.

The primary alternatives to CRTs for television displays are liquid crystal displays (LDCs), developed initially in the Pittsburgh laboratories of Westinghouse and at the David Sarnoff Research Center (then owned by RCA) in Princeton, New Jersey. George Heilmeier and Richard Williams of the Sarnoff lab first put forward in 1963 the idea that liquid crystals could be used for displays. Jim Fergason at Westinghouse began to pursue his own approach to LCD's in 1964. Fergason left Westinghouse in 1970 to found a new company called Liquid Xtal, which later failed due to delays in obtaining patents. Peter Brody, also at Westinghouse, pioneered "active matrix" addressing of LCDs. Brody left Westinghouse in 1979 and two years later founded his own firm, Panelvision, which was sold to Litton Industries in 1985.

LCD technology was first applied to watches and calculators for relatively small monochrome displays of numerical data by companies like Citizen, Seiko-Epson, Texas Instruments, and Hewlett-Packard. Sharp introduced the first calculator with an LCD in 1973 [Hayes, 1991, p. 232]. LCD technology depends on the ability of liquid crystals to change the polarization of transmitted light in the presence of a small electric field. In a monochrome LCD with no levels of gray, each pixel is a dot of liquid crystal that can be switched on or off by applying voltages at the proper row and column positions on the edge of the display (a process called "multiplexing").[7]

Monochrome LCDs were scaled upward in the mid-1980s to be used in portable computers and miniature black-and-white televisions. Because of low brightness and low contrast, these displays were not initially very successful commercially, so "super-twist" displays and a variety of new forms of backlighting were developed to make them more commercially viable. Multiplexed color LCDs have been developed subsequently for many applications, including hand-held televisions. Again, low brightness and contrast initially limited sales of these displays. The latest-generation devices are brighter, and they have been used successfully in a variety of applications.[8]

More recently, color LCD technology has moved beyond multiplexing toward "active matrix" addressing of pixels. An active-matrix LCD (AM-LCD) has a transistor on the glass panel next to each liquid crystal dot that switches it on or off. Whenever a dot is switched, it stays on or off until it is switched again. An active-matrix display can respond faster to updated image information than can a multiplexed display because it does not have to address pixels that remain the same from one frame to the next. This makes active-matrix displays much more attractive than multiplexed displays for high-information-content applications.

While AM-LCDs are the main competition to CRTs in advanced displays, a few additional candidates need to be mentioned: electroluminescence (EL), plasma display panels (PDP), vacuum-fluorescent displays (VFD), field-emis-

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[7] If the LCD has one or more levels of gray, gray-scaling is achieved by varying the voltage applied.

[8] The latest version of super-twist technology is called "triple super-twist nematic" (TSTN). A firm called InFocus Systems, based in Beaverton, Oregon, uses TSTN multiplexed LCDs to make direct-view and projection LCDs. The manufacturing of these LCDs is done by Kyocera and Seiko-Epson.

sion displays (FED, also called cold cathode or microtip displays), light-valve projectors, and laser projectors.[9] Light-valve and laser projection are both alternative methods for image projection, while EL, PDP, and FED technologies are useful mainly for producing direct-view flat-panel displays. U.S.-owned firms may be ahead of or at least competitive with Japanese firms in some of these technologies, but Japanese firms are well ahead in both CRT and AM-LCD technologies—particularly in the cumulative expertise they hold in applications and volume manufacturing.

Why LCDs Will Win the Market

Of the many emerging technologies, LCDs are most likely to triumph in the market. First, LCD technology is superior to any foreseeable alternative. Second, LCD production is backed by huge sunk investment and accumulated learning (especially in Japan). On the technology score, LCDs are rugged with relatively long lifetimes and a wide operative temperature range. They are also capable of high-resolution and color display with acceptable contrast and speed, and they consume very little power. They can be made very flat, and they are compatible with existing silicon chip technology for support and driver circuitry. They also have no apparent negative health impacts from electromagnetic fields. In terms of growth, LCD technology finds itself on a rapid learning curve, backed by a long accumulation of production experience, and supported by annual volumes in the millions from calculator, toy, portable computer, and hand-held TV applications. In fact, Japanese firms are so certain this technology will succeed that they have invested several billion dollars in new production facilities to make LCDs a fait accompli in the market.

No other alternative can boast as many technological advantages or as much sponsorship. LCDs will prove daunting to any challenger technology, including the well-established CRT. In the past, the main advantages of CRTs over LCDs were their greater resolution, brightness, higher contrast, and wider viewing angle under various levels of ambient lighting. But the problems of resolution, brightness, contrast, and viewing angle in LCDs have now been solved. The only problem that remains is size. With the exception of some experimental systems, direct-view AM-LCDs at the moment remain limited to less than 14 inches diagonally.[10] But the size of AM-LCDs is increasing incrementally at a few centimeters per year. When the size problem is eventually solved, as it will be in less than ten years at current rates of improvement, the main difference between CRTs and LCDs will be price.

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[9] Note that these alternatives, although they show the most promise for commercialization, are a small portion—probably less than 10 percent—of the experimental approaches to new display development.

[10] Toshiba and IBM have publicized their 14-inch AM-LCD, but have not shown it in public. Sharp has marketed an LCD projector for NTSC signals that projects a 50-inch image. Sharp and Sanyo have demonstrated prototype high-resolution LCD projectors, but neither appears to be ready for commercialization. A 19-inch EL flat panel is being manufactured currently by Planar Systems for Digital Equipment Corporation. Large color PDPs were demonstrated in May 1991 at the Society for Information Display by three different firms: Mitsubishi (33-inch), Thomson (23-inch), and Photonics Imaging (17-inch). Electroplasma demonstrated a 19-inch monochrome PDP at the same show. Plasmaco showed a very-large monochrome PDP at the same show.

CRTs are cheaper to produce than LCD flat panels of equivalent size. A color CRT for a 14-inch television cost around $40 to $60 to manufacture in 1992. A 14-inch color AM-LCD for a laptop computer costs between $1500 and $2000 to manufacture in that same year [Roberts, 1992]. Large CRTs are much more expensive than smaller ones. For example, a CRT for a 38-inch direct-view television costs around $1000 to manufacture, partly because of the lower volumes but also because of lower yields. The glass content of a large CRT tends to make it very heavy and hard to handle. In addition, special shadow masks and electron guns are necessary in larger CRTs. Small but bright monochrome CRTs for projection televisions are also quite expensive, but still considerably less expensive than AM-LCDs for LCD projectors.

The advantage of direct-view AM-LCDs and other flat-panel displays is mainly in compactness and lower power usage—and therefore in portability. In addition, most flat-panel displays produce no electromagnetic emissions. These qualities are particularly desirable in portable televisions and high-end portable computers and workstations. The market for portable electronic devices has grown very rapidly in the last ten years. Dataquest projects that the percentage of computer-based displays that are flat panels rather than CRTs will increase from 13 percent in 1992 to 46 percent in 1995 [Roberts, 1992]. Flat-panel displays cannot compete yet with CRTs in markets for inexpensive televisions or desktop computer displays. When large-area flat panels come to match CRTs in brightness, contrast, and viewing angle, and can be manufactured at reasonably low prices, then the advantages of compactness and low power usage will permit them to displace CRTs in a wider variety of applications.

One estimate of large-area flat panel costs comes from Eiji Taneko of the Giant Electronics Corporation of Japan. Taneko predicts that his company will be able to market a full-color 40-inch AM-LCD at around $1000 per unit in the year 2000. Barring a breakthrough in CRT manufacturing technology, this will make AM-LCDs quite competitive with CRTs at that size [Taneko, 1991].

LCD DOMINANCE AND THE ARCHITECTURE OF SUPPLY

As LCDs win in the market, a few major Japanese firms—especially Sharp, Matsushita, Hitachi, Toshiba, and Seiko-Epson—are coming to dominate the development of advanced displays. These firms are, of course, vertically integrated producers of electronics components and systems and are likely to be predominant suppliers of integrated display systems. As these firms come to dominate in the market, they will shift the character of the supply base in electronics, making it less accessible for other firms in the industry.

The danger is that these firms—a few vertically integrated, oligopolistic suppliers whose production activities and ownership are concentrated in Japan—will increasingly be in a position to dictate access to underlying electronics technologies, their quality and price, and the speed with which users can incorporate them into new products. U.S. systems firms that depend on these suppliers for displays would then be vulnerable to unfavorable prices, delayed or erratic deliveries of the latest devices, and other predatory behavior. Such practices may not necessarily be illegal, though they would provide strong competitive leverage in the market. Many firms, including U.S.-owned companies, have engaged in such practices when they were in the same position. In both DRAMs and in laptop LCD panels, there have already been incidents that bear out this prediction.[11]

Indeed, given the nature of this technology and the markets that support it—involving scale and learning economies, oligopoly, and strong first-mover advantages—it would be surprising if Japanese firms resisted the temptation to engage in predatory behavior. Their aims would be to reduce the amount of competition abroad, prevent new entry, and entrench their hegemony. For example, predatory pricing could limit their foreign display competitors to low-volume, niche markets. This was, in fact, precisely the problem that led to the positive findings by the Department of Commerce and the International Trade Commission on the antidumping petition filed against Japanese display manufacturers by the Advanced Display Manufacturers of America (ADMA) [Hart, 1993]. Such predatory behavior would significantly shape the underlying architecture of supply in component technologies.

In turn, a restrictive supply architecture will create severe problems for U.S. systems firms whose strategy depends on an open, accessible architecture for supplying components. Its thread is already having a significant impact on the corporate strategies of U.S.- and European-owned firms, and on U.S.- and European-based production activities. Several examples will suffice to demonstrate the implications. IBM has moved development of notebook and smaller computers out of the United States to its IBM-Japan subsidiary because that is the only place that guarantees access to the appropriate skills and necessary technologies. For similar reasons, Philips has moved development of hand-held TVs out of Europe to its Marantz subsidiary in Japan.

Very few other systems firms have the resources and domestic Japanese market presence to follow suit. Others, including Apple and Compaq, have had to form precarious alliances with competitors (Sony and Citizen Watch, respectively) in order to get access to the needed technology and skills. And even if individual firms manage to adjust successfully, the danger for the domestic U.S. economy is that it would increasingly lose the locus of activities that underpin modern electronics—and with it, eventually, most of the relevant component know-how.

As the supply architecture for displays shifts, there are likely to be three significant impacts on the U.S. economy. First, there will be a significant loss of know-how in component manufacturing activities. Second, there will be a progressive loss of new market opportunities. Third, the competitive dependencies that result will undermine the existing competitive strengths of U.S.-based firms. The overall result will be a significant diminution of electronics capabilities in the United States—perhaps a relegation of the United States to second-class status in the industry. Each of these major impacts is worth a closer look.

High-Resolution Displays Will Dominate Supply

Because buyers are willing to pay a premium for ever-flatter, more compact displays, high-resolution displays (HRDs) are pushing the limits of the associated manufacturing technologies. There are significant impacts on the types

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[11] On problems with DRAMs, see [1990, p. 66]. On the LCD incidents, see Advanced Display Manufacturers of America.

of manufacturing equipment required to manufacture AM-LCDs; on the new, high-volume, processing capabilities high-resolution flat panels require; and on related manufacturing technologies like packaging, materials, and other kinds of components.

Flat-panel manufacturing requires the use of lithography and deposition equipment, including steppers developed originally for semiconductor manufacturing and adapted for flat-panel production. Methods used to increase yields in semiconductor production—such as clean rooms and statistical quality control—are also used in flat-panel production. High-volume production of flat panels, therefore, can be a driver for innovation in semiconductor production equipment. This innovation is not likely to be in the area of making smaller line-width devices, but rather in equipment for large-area processing.

The next generation of flat-panel manufacturing equipment will be aimed at integrating displays with LSI, VLSI, and ULSI circuitry on large glass panels.[12] Steppers and advanced lithography equipment for semiconductor manufacturing are designed for relatively low variance in the size of objects on relatively small circular silicon or gallium arsenide substrates.[13] By contrast, steppers and deposition equipment for integrated displays will have to handle larger variation in the size of objects on a much larger rectangular glass substrate. The approach of companies like Nikon and MRS Technology is to adapt stepper alignment machines to the larger areas. The approach of the Giant Electronics Corporation in Japan—and perhaps the economical winner in the future market—is to move away from steppers to printing technologies.

Deposition equipment for semiconductors has much in common with deposition equipment for flat panels. Both need to be able to deposit thin films of metal and metallic compounds on substrates. Since many flat panels have multiple layers of thin-film oxides, deposition equipment optimized for oxide deposition may be better for flat-panel processing than the nitride deposition machines used in most wafer fabs. But whatever machines are eventually used, the underlying thin-film deposition technologies remain much the same.

The substrates for semiconductors are usually either silicon or gallium arsenide, while the substrates for flat panels are usually glass. Glass-handling robots, which use the same technologies as wafer-handling robots (for semiconductor or flat-panel production lines) but have been modified to deal with the larger size and different physical properties of glass panels, are being marketed.

In other words, while manufacturing equipment for advanced displays will be different in some respects from that for semiconductors, there will continue to be many common features as well. One can expect that firms that manufacture both integrated displays and advanced integrated circuits (ICs) will have some advantages in overall electronics manufacturing technology over those that specialize in displays or ICs alone. Similarly, equipment firms that have customers for both IC production machines and flat-panel equipment may do better than equipment firms that are limited to one or the other market.

Whatever the outcome with individual firms, the architecture of supply of

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[12] Large Scale Integration (LSI), Very Large Scale Integration (VLSI), and Ultra Large Scale Integration (ULSI).

[13] Leading-edge wafer processing equipment is geared to 8-inch wafers.

the underlying machinery will shift to favor those who produce for both IC and display uses. There will also be a shift in the locus of relevant process know-how as AM-LCDs come to dominate. Fabricating AM-LCDs is somewhat more difficult than manufacturing conventional LCDs because semiconductor circuitry and liquid crystals must be deposited accurately and reliably on the same glass substrate. In the 1970s, the Casio Corporation developed a new technology to do this called amorphous-silicon processing. Casio originally applied amorphous-silicon to the manufacturing of calculators. Casio's credit-card calculators, made with this process, were very successful in the market because of their small size and low price.

Amorphous-silicon (a-si) processing involves the deposition of thin films of metals and metallic oxides—using an impure form of silicon crystal that has certain desirable properties—on a glass substrate that also contains the liquid crystal pixels. A-si technology has evolved considerably since its introduction. Initially, there were significant problems of electrical leakage in a-si circuits. These were solved by adopting a variety of new deposition techniques. A-si technology has proven to be reliable in high-volume manufacturing, even though yields are not as high as manufacturers would like. Most current research on a-si technology is aimed at reducing manufacturing costs by increasing yields: for example, by reducing the number of masks needed to etch circuits and by improving alignment techniques for large panels.

A-si may be replaced eventually by poly-silicon (p-si) processing technology because p-si circuitry can be more complex than a-si circuitry. The ability to place driver and logic circuitry on the glass substrate of the display panel using p-si technology may make it possible to reduce interconnection costs and increase yields of assembled displays. The main problem with p-si processing is that it requires higher temperatures than a-si processing; the negative effects of high temperature on the glass itself can negatively affect manufacturing yields. Glass that holds up well under high-temperature processing is considerably more expensive than low-temperature glass.

Such processing innovations are likely to be complemented by packaging innovations. Display manufacturers are leading innovators in advanced packaging techniques like "chip-on-glass" (COG), tape-automated bonding (TAB), and flexible circuits [see, e.g., Reinke, n.d.; Prasad, 1989, ch. 1]. COG is used to put driver circuitry on the glass substrate. This is done by bonding an unpackaged integrated circuit chip to the panel and then connecting it to the display with automated wire-bonding equipment. TAB techniques can be used for placing the chip in the proper location on the glass substrate; this is called "TAB-on-glass" or TOG. Flexible circuits are used on the ribbon cables connecting the display to the rest of the system. These and other foreseeable packaging technologies are likely to be applicable to a wide variety of electronics systems.

In similar fashion, a range of complementary materials and component technologies are likely to benefit from their synergy with advanced displays. These include battery technology for portable applications; a range of ICs including CCDs (charge-coupled devices), DSPs (digital signal processors), and RAMs (random access memories); light sources (for back-lighting); and precision mechanical components.[14] As the next subsection suggests, emerg-

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[14] For a detailed discussion of the IC impacts, see U.S. Congress, OTA [1990, pp. 63–68].

ing component technologies associated with speech, handwriting, and touch recognition are also likely to be affected by progress in displays. Finally, innovative applications of chemical technologies are also likely as the need for better latching, contrast, and temperature-range performance increases.

On top of these technological impacts, integrated displays will be more compact, more functional, and eventually cheaper than displays with no integration. Systems manufacturers who are successful in integrating system circuitry onto display panels may therefore displace manufacturers who are not. There will be major manufacturing advantages for firms integrating at least some of the electronic circuitry of the system onto the display panel. Even though microprocessors and memory devices are likely to remain on separate circuit boards, driver, logic, and testing circuitry can at least be integrated with the display. This reduces the cost and increases the reliability of interconnecting the display with the rest of the system.

One possible historical analogy for the importance of integrating system circuitry onto the display is the failure of most U.S. consumer electronics manufacturers to use integrated circuits or to speedily reduce the number of circuit boards in color television sets in the 1970s, in stark contrast to their Japanese competitors. The inability of most U.S. producers to take advantage of the cost-reducing and reliability-enhancing features of circuit integration and manufacturing simplicity made possible by ICs helped to accelerate their competitive decline [Hart, 1991].

Integrated Displays and New Markets

Systems with integrated displays will not only displace systems with plain displays in existing markets; they will open up new markets that did not exist before. Greater portability, low power usage, and compactness will combine with relatively lower production costs to expand demand. Integrated displays will permit individual users to carry around with them general-purpose computers that were previously immobile and special-purpose computers that were not previously economical to build. A range of existing product markets will also be transformed into new market opportunities by the addition of display system capabilities.

The rapid success of laptop and now notebook computers is an indication of the potential size of these new markets.[15] Even before the laptop computer, one can argue that the firms that succeeded in integrating simplier displays with circuitry (as Casio did with watches and calculators) were able to win market share in highly competitive markets. These early integrators may have some advantages in the next round because of their experience with COG, TAB, and flexible circuits.

Currently, several workstation manufacturers are marketing personal workstations with color LCD flat-panel displays on the assumption that people will pay a premium for compactness in highly functional systems. Integrated displays will have a significant impact in that realm as well. U.S. firms are overwhelmingly dependent on Japanese firms for the LCDs that make laptop, notebook, and palm-top systems possible. Japanese firms, therefore, are generally well positioned to take advantage of integrated displays—in both the component and end-product markets.

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[15] On the rapid growth of the laptop market, see Pollack [1990].

Smarter cellular telephones, more functional inventory-tracking devices, faster financial telecommunicating devices—all will become easier and cheaper to make with the development of integrated displays. Many entirely new and unpredictable applications of microelectronics technology are likely to arise with the integration of displays with systems. Not all the things that large systems do will be duplicated in smaller systems—for example, the centralized management of real-time, on-line databases for large organizations. Nevertheless, the evolution of more powerful computing devices in smaller packages is likely to make it possible to decentralize anything that now is centralized for reasons of lowering computing costs only.

Many office machines and consumer durables will be using flat-panel displays as visual interfaces in order to make it easier to use the product or to diagnose problems. Examples of this trend can be found in photocopiers, key systems (multiline telephone systems for offices), laser printers, and fax machines. Thus, the current generation of photocopiers uses LCDs to give users feedback on the nature of the job they are doing and to help them correct a problem in the system (e.g., paper jams and toner refills). The graphics display can make it possible to add new functions to the machine without overburdening the user with problems of learning how to use the machine. It can also probably reduce the tendency of users to call the company to correct minor problems.

In short, flat-panel displays can enhance the value to users of a wide variety of products. The more difficult the product is to operate without instructions, the greater the need for displays to provide guidance and diagnostics. Thus, displays will become increasingly important for many consumer durables and office machines, even those products that have not previously included displays. Capturing these new opportunities will require timely access to the necessary display technologies at a reasonable price. Such access will become more difficult as the supply architecture becomes even more restrictive.

Subverting U.S. Strengths: GUI and Multimedia

Up until now, existing U.S. strengths in system architecture and software, product definition, and marketing, appear to have provided a powerful means of bargaining to maintain access to necessary technologies—in essence, of keeping open a supply architecture that would otherwise tend to become restricted (more about this below). This can be seen, for example, in Apple's ability to use control over its graphical user interface (GUI) to lever its portable Mac deal with Sony, and Hewlett-Packard's control over its laser printer driver software to lever its relationship with Canon for supply of the laser printer engine. Nonetheless, integrated display systems and a restrictive architecture of supply will also create challenges to "soft" U.S. strengths. The stakes can be seen in potential impacts on GUIs and multimedia computing.

Graphical user interfaces (GUIs) are central to the current competition among operating systems for microcomputers and workstations. The Macintosh GUI, for example, is widely recognized as a key to the success of the Macintosh as an office machine because it lends itself to easy training of new personnel. The combination of a high-resolution monitor with a "mouse" (a kind of pointing device) and a relatively standard set of graphical symbols for starting and ending programs (also for editing, cutting and pasting, and drawing) makes the Macintosh operating system easier for novices than those using text-only displays and keyboards for input.

So important have highly functional, user-friendly GUIs become to success in the market, that all major computer players have emulated the Macintosh approach—IBM with its Presentation Manager for OS/2, Microsoft in its Windows environment, and major workstation producers with GUIs like Sun's SunView and Hewlett-Packard's New Wave (not to mention competing standards like Motif and X Windows).

In order for GUI's to make computers more accessible and functional, they need to be used in conjunction with high-resolution displays, preferably with color. High resolution permits a great deal of detailed information to fit on the display and allows the computer to work well with a wide range of display sizes. Color helps the user to differentiate between different types of information on the screen. Because of the extensive use of "windows" in GUIs to represent the various tasks that the computer is performing at any given moment, GUI workstations are easier to use when the display is larger than the conventional 14-inch desktop display.[16]

GUIs with full-motion video and digital audio capability—a combination now increasingly referred to as multimedia computing—may prove to be especially useful for training people who are using computers for the first time and who may be resistant to learning from screens that display only words, numbers, and other static symbols.[17] Video and audio capability will also make desktop machines more functional for advanced users. A mutually reinforcing relationship is thus established between the development of advanced displays and electronic systems manufacturers trying to make their products both easy to use and highly functional. High-information-content (HIC) displays have the capacity to exploit the potential of multimedia computing, and, in the end, the ability of systems manufacturers to produce functional multimedia will depend on the quality of displays they can incorporate.

In short, whatever their "soft" strengths, systems manufacturers must still have advanced displays in their products. For them, the threatened shift in the supply architecture from open to restrictive is hugely problematic: It matters not just how much the displays cost, but whether the most advanced displays are available in a timely manner and whether it will be possible to work with suppliers of displays in integrating system circuitry. If the displays are priced higher on the merchant market than they are for internal use, or if the latest displays are not available or do not permit codesign or joint manufacturing to minimize final product costs, then an important advantage will accrue to those vertically integrated firms that manufacture both displays and systems. Almost no existing U.S. or European systems firm manufactures displays; all of their would-be challengers in Japan do.[18]

If the concerns enumerated above are real, why have non-Japanese firms who are dependent upon their Japanese competitors for display technology—from Taiwanese and U.S. PC makers to U.S. workstation vendors—been

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[16] According to Booz-Allen and Hamilton [1990, p. 25], 60 percent of the displays sold by DEC are color and 70 percent of the systems sold by Sun have color displays.

[17] This claim has been made by Intel in explaining its purchase of the digital video interactive (DVI) technology pioneered by a group at the David Sarnoff Research Center in Princeton. It is also the position taken by John Sculley of Apple Computer, who calls it P3TV (Paradigm Three Television).

[18] IBM—an important exception—is manufacturing AM-LCD displays jointly with Toshiba.

so successful in recent competition? In other words, why hasn't a more restrictive supply architecture in displays translated into overwhelming competitive leverage for Japanese producers?

First, U.S. and other firms have benefitted from several accidents of timing. On the one hand, the Japanese display industry (as detailed in the next section) is still composed of numerous suppliers who are competitively jockeying for market advantage. This means that the architecture of supply, while geographically concentrated, is still relatively open. On the other hand, the domestic Japanese economy is extremely troubled at the moment and, with the collapse of the asset bubble, Japanese firms are extremely sensitive to return-on-investment considerations. Under these conditions, Japanese companies have been extremely willing to deal internationally, both to earn higher returns and to develop risk-reducing joint activities, one cost of which has been access to their display technologies.

Second, governments outside Japan have helped indirectly to maintain an open and accessible supply architecture in component technologies. The U.S. government's policies supporting Sematech, the U.S. chip industry's cooperative manufacturing technology development vehicle, and the U.S.–Japan Semiconductor Trade Agreement (with its emphasis on Japanese market access), have been complemented by domestic policies in Korea, Taiwan, and Europe that have fostered new competitive entry in components markets. While none of these policies has directly addressed the supply architecture in displays, together they have provided a powerful signal and demonstration effect for Japanese display producers who realize that their competitive behavior is likely to be as closely scrutinized as in chips.

Third, and just as important, after a decade of being beat up in the market, some U.S. electronics firms have developed successful strategies in response. They have been fleeter afoot in responding to unpredictably shifting market opportunities in electronic systems—something the consensus-oriented, slower-moving Japanese firms have found difficult to manage successfully. In other words, the resources and manufacturing/engineering strengths of Japanese firms have been less of an advantage in markets whose line of technical advance is neither certain nor incremental in the manner of memory chips or displays. U.S. firms have been able to use their "soft" skills—product definition/design, software, systems integration, marketing—to set the terms of market competition (e.g., through new RISC processor architecture in workstations, or new distribution channels like Dell's mail-order approach for marketing PCs). Japanese firms have found that those market-defining "soft" skills are much harder to acquire successfully than the hardware capabilities they mastered in the 1980s.

The significant question, of course, is will these circumstances endure? Will they continue to prevent the emergence of a restrictive supply architecture in electronics? There is good reason to believe that the existing beneficial situation will not long endure. The accidents of timing will certainly change. There will eventually be a shakeout among Japanese display producers with a few players coming to dominate the market. Indeed, the current turmoil in the Japanese economy seems likely to accelerate this shakeout. When the Japanese economy recovers, there will be a strong domestic market again for the surviving firms. We can predict with similar certainty that Japanese

Table 1. Demand shares of flat-panel displays by type of end use, 1989 and 1996.

Type of end use	1989	1996
Consumer	39.0	36.0
Computer	25.0	35.0
Business	16.0	13.0
Industrial	6.0	7.0
Transportation	11.0	6.0
Communications	2.0	2.0
Military	1.0	1.0
Total	100.0	100.0

Source: Stanford Resources, Inc.

firms will eventually adjust to the most successful of the new American strategies, just as U.S. firms did to Japanese strategies—that is, after all, the perpetual dance of market competition.

For these reasons alone we conclude that the current situation is not stable. Shifts in governmental policies are likely to make it even more unstable. Foreign industrial policies might continue to push toward supply-base openness, but they might also result in limited or preferential access. U.S. policy has rarely displayed much consistency in this area. It is more often a hostage to the crisis of the moment. If supply-base openness is to be maintained into the future, U.S. policy may have to pursue that end self-consciously. We will return to this question in the concluding section.

It is, thus, an open question whether the supply architecture of display technology will remain open or will become ever more restrictive. The only guarantee of continued access is significant U.S. participation in the industry. Such participation needs to be a priority for any nation wishing to remain on the cutting edge of electronics. But what does significant participation entail? Must U.S.-owned firms actually produce advanced displays? Or is it necessary only that such production be located in the United States? Is it simply a matter of assuring access in a timely manner at reasonable prices to the integrated display-system products and technologies produced abroad? The answers to these questions depend upon the current status of market competition, to which we now turn.

JAPANESE LEADERSHIP IN ADVANCED DISPLAY MARKETS

The current markets for advanced displays are strongly dominated by Japanese firms. As pointed out earlier, these firms are mostly large, vertically integrated electronics firms, although a few like Hosiden are smaller and more specialized. They largely control the world market for flat-panel displays, valued at $3.2 billion in 1989. This encompasses all sorts of flat panels, including the simplest monochrome LCDs. That market is projected to grow to $11.2 billion by 1998. Table 1 shows breakdowns of demand for flat panels by type of end use. Stanford Resources believes that demand for flat-panel

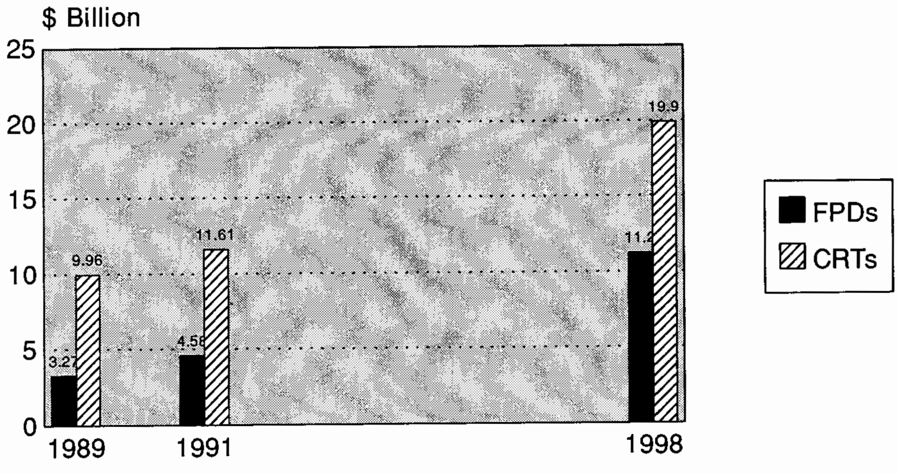

Figure 1. Worldwide display market forecast flat panel technologies vs. CRTs. Source: Stanford Resources, Inc.

displays will grow more rapidly in the computer industry than in any other end-user industry.[19]

The world market for high-information-content (HIC) displays (i.e., displays with greater than 100,000 pixels) was around $9.6 billion in 1989—which was about 83 percent of the world display market.[20] Television and high-resolution computer monitors are the two largest market segments in the HIC display market. The flat-panel portion of the HIC display market was around $670 million in 1989 (7 percent) and was shared between LCDs and plasma display panels (PDP) with EL displays accounting for only about 2 percent of the FPD total.

The HIC display market is projected to grow to around $23 billion by 1996. Stanford Resources predicts rapid growth in flat-panel HIC displays to $6.9 billion, or 30 percent of the HIC display market by 1996 (see Figures 1 and 2).[21]

CRT displays currently dominate high-information-content display markets in mid-size televisions and in monitors for desktop computers, dumb terminals, and workstations. Flat-panel displays (FPDs) dominate in laptop computers and LCD televisions—products that cannot be made with CRTs.

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[19] This belief is supported by the projection of Nikkei Business Publications Electronics Group, in a November 1989 publication, that 24 million of the 40 million personal computers to be sold in 1995 will use LCDs—8 million AM-LCDs, 8 million multiplexed color LCDs, and 8 million monochrome LCDs. See TechSearch International [1990], p. 1.

[20] In this part of the study, advanced displays and high-information-content displays are treated as synonyms. There is reason to argue, however, that 1 million pixels rather than 100,000 should be the boundary between advanced and conventional displays, since HDTV-quality video requires that many pixels. VGA monitors for computers are capable of displaying 300,000 pixels, and so would be considered to be high-information-content displays under the Stanford Resources' definition.

[21] Stanford Resources, Inc. figures cited in Booz-Allen and Hamilton [1990, pp. 10–11].

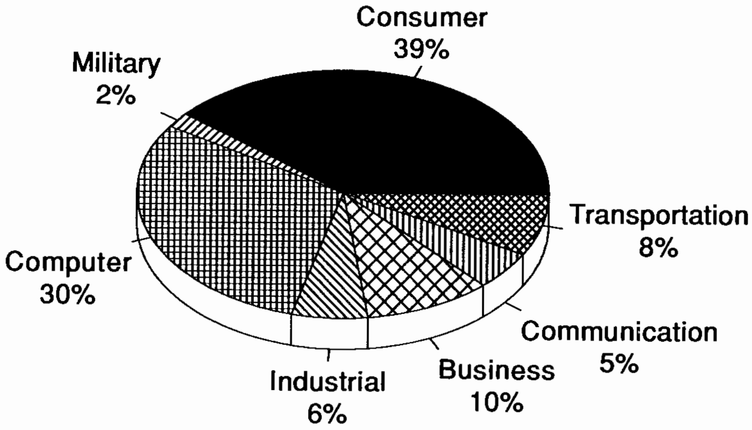

Figure 2. Worldwide flat panel display market percent shares of total market of $4.58 billion by types of application, 1991. Source: Stanford Resources, Inc.

All current LCD-TVs have small (less than 6-inch diagonal) LCD displays. Over 90 percent of portable computers have either LCD or PDP displays. Most of these are so-called monochrome half-page variety, which are 10-inch diagonal.

In the near to midterm future, advanced displays will be most important in televisions, portable computers and workstations, and military electronic systems. The major television manufacturers in Japan and Europe are developing larger LCD displays. In Japan, the goal of one government-industry research effort is to build a one-meter diagonal active-matrix LCD.[22] Digital Equipment Corporation is currently marketing a workstation with 19-inch high-resolution, monochrome EL display, produced for them by Planar Systems.[23] In the next ten years the demand for advanced displays will grow more rapidly than the demand for high-information-content CRTs because of their greater compactness, portability, and lower levels of electromagnetic emissions. Prices of large-area color flat panels will remain higher than those for comparable CRT displays for at least a decade, but for the relatively smaller large-area video projector market, LCD projectors may be considerably cheaper in just a few years.

Major Japanese Producers

Japan controls more than 90 percent of the world market for AM-LCDs, 69 percent of the world market for PDPs, and 29 percent of the world market for EL displays [U.S. Congress, OTA, 1990, p. 70]. In addition, Japan controls well over 90 percent of the world market for multiplexed LCDs.[24] These strengths in advanced flat-panel display production are based on a solid

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[22] This effort is part of the Giant Electronics Technology program funded jointly by the Japanese Ministry of International Trade and Industry (MITI) and participating firms.

[23] Interview with James Hurd, Planar Corporation, Beaverton, Oregon, July 6, 1990.

[24] David Mentley, Stanford Resources, telephone conversation, February 24, 1992.

Table 2. Major Japanese firms in flat-panel display markets.

Company	Technologies	Estimated 1989 shipments ($ millions)
Citizen	LCD	75
Fujitsu	PDP	45
Hitachi	LCD	210
Hosiden	LCD	50
Kyocera	LCD	36
Matsushita	LCD, PCP	242
NEC	PDP	19
Oki Electric	PDP	28
Optrex	LCD	211
Sanyo Electric	LCD	87
Seiko-Epson	LCD	187
Sharp	EL, LCD	241
Toshiba	LCD	168

Source: Stanford Resources, Inc.

commitment by at least ten major firms to invest in display research and production facilities for long-term payoffs.

The ten largest Japanese producers of FPDs are Matsushita, Sharp, Optrex, Hitachi, Seiko-Epson, Toshiba, Sanyo Electric, Seiko Instruments, and Citizen Watch (see Table 2). Other producers are Fujitsu, Kyocera, Stanley Electric, Shimatori Sanyo Electric, Alps Electric, and Futaba Electronic Industries. Sharp, Hitachi, and Optrex are the largest producers of high-information-content LCD displays. High-volume production of high-information-content LCDs is still mainly in multiplexed LCDs. Optrex, for example, manufactures only multiplexed LCDs for use in equipment panels and cars. AM-LCDs are still too expensive for most high-volume applications, with the notable exception of hand-held TVs and high-end laptop computers. However, all the major systems firms and few smaller firms have made large investments (in the $100 to $200 million range) in AM-LCD production facilities; it is clearly their intention to shift into high-volume production of AM-LCDs as soon as possible.

Japanese firms are approaching the switching of AM-LCD pixels from two

Table 3. Recent investment in active-matrix LCD production facilities in Japan.

Company	$ Millions	Location	Technology
Alps	33	Iwaki	TFT
Fuji-Xerox	80	Ebina	a-Si TFT
Hitachi	134 + 67/yr	Mobara	a-Si TFT
Matsushita	230	Osaka	p-Si TFT
NEC	67	Kagoshima	TFT
Seiko-Epson	40	Nagano Pref.	TFT
Seiko Instruments	20	Akita Pref.	Diode Matrix
Sharp	447	Tenrie/Mie	a-Si TFT
Toshiba/IBM	134	Himeji	a-Si TFT

Source: Stanford Resources, Inc.; U.S. Congress, OTA [1990, p. 71].

Table 4. Japanese spending on active-matrix LCDs, as of 1990–1992.

Company	Amount ($ millions)
Sharp	700
Sanyo	560
Matsushita	350
Hitachi	210
Hosiden	140
Toshiba/IBM	140
Mitsubishi	70
NEC	70

Source: Nikkei Sangyo Newspaper Survey as cited in Corcoran [1991, p. 114].

main directions: thin-film transistors (TFT) and metal-insulator-metal (MIM) diodes. TFT AM-LCDs are more difficult to make but are probably better suited to faster and higher-resolution color displays. MIM AM-LCDs are easier to produce, and therefore lower in price, but less well suited to color, faster speeds, and higher resolution [TechSearch International, 1990, p. 11].

Sharp and Hitachi are clear leaders in TFT AM-LCDs. Hitachi is marketing a very high quality 10-inch color AM-LCD for laptops and portable workstations. Sharp is selling 6-inch TFT AM-LCDs for televisions and 10-inch high-resolution monochrome AM-LCDs for computer applications. Sharp has marketed a second-generation LCD projector called the XV-120. The imaging source for this projector is a single, full-color TFT AM-LCD. Toshiba is using its joint venture with IBM to become a player in the AM-LCD area, oriented toward use in laptops and portable workstations. While originally behind Sharp and Hitachi in this area—some high-end models used Sharp displays—its venture with IBM appears to be narrowing the gap considerably. The venture's latest 10-inch color display, used in Toshiba's high-end notebooks, is extremely sharp and appears to be as good as anything on the market.

Hosiden is a smaller firm that previously specialized in the production of switches and connectors.[25] Hosiden was an early developer of AM-LCD technology, starting its research around 1979 with financial support from the Ministry of International Trade and Industry (MITI). Hosiden's main customers for AM-LCDs in Japan have been Matsushita Electronic Industrial (MEI), Nippon Telegraph and Telephone (NTT), and the Japan Aviation Electronics Industry (JAEI). Hosiden is now the main supplier of AM-LCDs to Apple Computer for use in its portable Macintosh computer.[26] Hosiden began to produce 10-inch color AM-LCDs in a facility at Seishin designed to produce

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[25] See Table 2 for Hosiden's place among Japanese LCD manufacturers. Hosiden's current sales average between $50 and $100 million per year (50 billion yen in 1990), according to David Mentley, Stanford Resources, telephone conversation, February 24, 1992.

[26] The Macintosh Model 170 Powerbook uses a monochrome active-matrix display. The Powerbook has sold much better than an earlier portable, the Model 145, which has a passive matrix display, despite a price premium of around $1200 [Gulick, 1992, p. 11].

about 30,000 units per month early in 1990. Hosiden is focusing on the computer market and will not produce consumer products or projection displays. They use custom-made production equipment and are trying to maintain their lead through innovations in process technology [see *Japan Company Handbook*, 1990, p. 692; Ogisu, 1989]. However, Hosiden's considerably smaller scale makes it less likely that the company will be able to keep up with the investment race.

While the main Japanese R&D effort focuses on incrementally improving multiplexed LCDs and developing new AM-LCD technologies, a number of firms have invested in alternative flat-panel and projection technologies. Futaba Corporation is the most important player in vacuum fluorescent displays (VFDs). Matsushita and Oki are competitors in the international markets for monochrome plasma displays. IBM uses Matsushita plasma displays in one of its PS/2 portable machines. Matsushita is active in research on ferroelectric liquid crystals for light-valve projectors and on field emission displays. Sharp is the only major Japanese firm in the EL market.[27]

Some of the firms that were initially quite strong in LCDs were watch and calculator firms like Casio, Citizen, and Seiko-Epson. While Seiko-Epson seems to have made the transition to HIC displays, innovating early and successfully in the technologies for integrating driver circuitry on the LCD substrate, Citizen and Casio have not done so well. But Seiko-Epson was unable to deliver as promised a blue-mode HIC display to a small California firm called Dynabook Technologies, so the latter switched to Hitachi.[28] Citizen and Casio have chosen not to develop AM-LCD [Ogisu, 1989, p. 4].[29]

The supply base for flat-panel manufacturing is stronger in Japan than in any other country. All the necessary tooling and materials activities are located in Japan, and at least one Japanese firm focuses on each of the developing technologies. For example: (1) Asahi and Nippon Sheet Glass make glass substrates for flat panels; (2) Nikon makes large-area steppers; (3) NEC Anelva makes dry etching equipment; (4) Nitto Denko makes color filters and polarizers; (5) Dai Nippon Printing and Toppan Printing make advanced printing equipment for large-area flat panels; (6) Japan Vacuum Technology makes Indium Tin Oxide (ITO) films for transparent conductors; (7) Canon makes mirror projection systems; and (8) a variety of firms make fluorescent backlights. Even where Japanese firms are not strong, as in the manufacturing of liquid crystal chemicals, gray-scale drivers, and high-performance glass, foreign firms have located in Japan or formed joint ventures with Japanese firms to service the local market. Examples of this phenomenon include Merck Japan, Texas Instruments Japan, and Corning Asahi Video.

Japanese Government Policies

Japanese government interest in high-resolution displays originally stemmed from a desire to improve existing computer monitors so that they could

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[27] Sharp briefly funded a small American firm called Amtel Video in its efforts to produce a white-light modulator called "crystal scan" (see later section on American firms).

[28] Interview with Dan Evanicky of DynaBook on August 14, 1990.

[29] Citizen is assembling a laptop model, an LTE, for Compaq in Japan; it uses super-twist LCD technology. In the future, it may move to AM-LCDs, or it may use improved super-twist LCDs. Telephone conversation with David Mentley, Stanford Resources, Inc., February 24, 1992.

display legible kanji and kana characters along with the usual ASCII characters. The Pattern Information Processing System (PIPS) program from 1971 to 1981 was the first major government program that included funding for high-resolution monitors and displays. PIPS focused mainly on the problem of electronically representing a sufficient number of easily recognizable kanji and kana characters. This work was crucial, however, for motivating the subsequent research on high-resolution displays. Total funding for the PIPS program was 22 billion yen, and most of the work was carried out at the Electro-Technical Laboratory, run by MITI's Agency of Industrial Science and Technology [Vogel, 1985, pp. 142–143].

With the transition in consumer electronics to high-definition products, the Japanese government has instituted a variety of R&D programs to support the work of the public broadcasting network NHK and manufacturing firms. Two programs are aimed directly at advanced displays: (1) a seven-year $100 million collaborative research program to build a one-meter diagonal color flat-panel display for HDTV; and (2) a similar program to support the development of a high-definition LCD projector. The flat-panel project is cofunded by MITI, the Ministry of Posts and Telecommunications (MPT), and the private firms that belong to the Giant Electronics Technology Corporation (GTC). The core corporate members are Dai Nippon Printing, Hitachi, NEC, Sharp, and Toppan Printing. Government funds derive primarily from proceeds of the sale of NTT shares, tobacco taxes, and motorboat racing fees. As mentioned briefly above, the GTC effort focuses on the use of printing technologies in conjunction with polysilicon processing techniques to manufacture large-area AM-LCDs. In typical and complementary bureaucratic rivalry, the projector project is funded by the Ministry of Posts and Telecommunications (MPT) [U.S. Congress, OTA, 1990, pp. 68–69].

The Japanese government understands that the manufacturers are already strong in this area, so the various agencies are not expending large sums of money. Nevertheless, they are trying to push the firms to develop larger displays so as to make it easier to sell the products associated with high-definition TV (HDTV). The research involved is ostensibly "precompetitive" in that the focus is on generic technological advance in displays and none of the items involved is near immediate commercialization. True high-definition LCD projectors are still several years away from introduction to the market; large-area AM-LCD flat panels are probably seven to ten years away from introduction.

Major European Challengers

Despite their established place in video consumers electronics, the major European electronics players are far behind the Japanese in the development of advanced displays. The major European firms involved in research on advanced display technologies are Philips, Thomson, Finlux (and its subsidiary, Lohja–now a division of Planar Systems), Thorn-EMI, AEG, Hoffmann-LaRoche, GEC, Barco, and Olivetti (in a joint venture with Seiko Instruments). Two national laboratories in France, CNET and LETI, have display research teams. In Germany and the United Kingdom, a number of university teams are working in this area as well. The two biggest players are the two consumer electronics giants—Philips and Thomson.

Philips is using its laboratories in The Netherlands (Eindhoven) to develop

AM-LCDs and driver circuitry for advanced displays. Philips recently demonstrated a 6-inch diagonal diode-addressed full-color LCD. It is not encouraging, however, that Philips has now moved development of small diameter LCDs out of Eindhoven to its Marantz subsidiary in Japan. This move is an acknowledgment of Philips' relative lag in commercialization of advanced displays. Perhaps more important, the move acknowledges that to access the best display know-how, a firm must acquire the skills and supply base now resident only in Japan. This new truth is also born out by IBM's similar venture with Toshiba (see below).

When Thomson purchased the consumer electronics operations of GE in 1987, it also acquired the GE process for making amorphous silicon AM-LCDs. These AM-LCDs developed by GE were designed for military applications rather than consumer applications. Thomson has continued to produce AM-LCDs for military applications and sells them in the United States through a joint venture called Sextant-Avionique. Thomson has pulled back from developing AM-LCDs for consumer products and has put its resources instead into AC-plasma and cold cathode displays, peripheral driver circuitry for AM-LCDs (work done mainly at the David Sarnoff Research Center in Princeton, New Jersey), and improved CRT technology.

There is a Philips-Thomson-Sarnoff research consortium for AM-LCDs under consideration at the present time. The negotiations for this consortium have been underway for over a year. It is likely that the consortium would apply the Thomson-Sarnoff work on peripheral circuitry to Philips' AM-LCDs, but unlikely that a viable venture will emerge from these negotiations, as both Thomson and Philips are currently suffering financial difficulties. The fact that the negotiations took place indicates that neither Thomson nor Philips is confident about their ability to produce AM-LCDs on their own.

Lohja-Finlux has developed some innovative EL displays. They are apparently working on using a cadmium selenide AM-LCD to drive an EL display. They have also been active in applying atomic layer epitaxy (ALE), a relatively new form of chemical vapor deposition, to the manufacturing of EL displays. Lohja-Finlux was recently acquired by Planar Systems, a small American firm that dominates world markets for EL displays.

The European Community has been funding research in high-definition technologies through the Eureka-95 program—the main participants being Philips, Thomson, Nokia, and ITT-Intermetal. Eureka-95 has been dedicated to the production of prototype equipment for European high-definition standards: 1250/50 for production and HD-MAC for delivery. In a clean division of labor, Thomson and Philips are working on the receiver technology, Nokia on the transmission equipment, and Intermetal on the HD-MAC chip-set. The Eureka project has been plagued by several political problems (especially resistance by several European broadcasters to the D-MAC standard) as well as the failure of several participants to meet technical development deadlines (notably Intermetal's problems delivering the promised chip-set). The Europeans are aware of their relative weakness in display technology and are trying to catch up to Japan, but like the American, and as the Eureka troubles indicate, they have a long way to go.

U.S. Efforts to Stay in the Game

As Table 5 indicates, the main U.S. firms involved in advanced display technologies are IBM, Xerox, Texas Instruments, Hughes Corporation, Tektronix,

Table 5. U.S. firms in advanced display businesses, 1990.

Company	Headquarters	Technologies
Amtel Video	Palo Alto, CA	white-light mod.
Bellcore	Red Bank, NJ	PDP
Cherry Display Products	El Paso, TX	PDP
Coloray	Fremont, CA	FED
Electro-Plasma	Millbury, OH	PDP
Greyhawk Systems	Milpitas, CA	X-Y laser addressed AM-LCD
Hamlin-Standish	Lake Mills, WI	AM-LCD
Hughes Corporation	Carlsbad, CA	light-valve
IBM	Armonk, NY	AM-LCD
Magnascreen	Pittsburgh, PA	AM-LCD
Nitor	San Jose, CA	laser projection
Optical Imaging Systems	Troy, MI	AM-LCD
Photonics Systems	Northwood, OH	PDP
Planar Systems	Beaverton, OR	EL
Plasmaco	Highland, NY	PDP, COG
Projectavision	Westbury, NY	LCD projection
Raychem	Menlo Park, CA	AM-LCD
Tektronix	Beaverton, OR	plasma-addressed AM-LCD
Texas Instruments	Dallas, TX	deformable mirror
Woodside Design	Sunnyvale, CA	VFD
Xerox	Palo Alto, CA	a- and p-silicon AM-LCD

Source: U.S. Congress, OTA [1990, p. 71]; interview materials.

Raychem (including its subsidiary, Taliq), Planar Systems, Greyhawk Systems, Optical Imaging Systems (OIS), Plasmaco, Photonics Systems, Magnascreen, Electro-Plasma, Cherry Display Products, Coloray, Amtel Video, Nitor, Hamlin-Standish, and Projectavision.

Except for the first four firms listed, all of these companies are small. The commitment of the larger firms to move to high-volume manufacturing is extremely limited. Of the smaller firms, few have the resources or technical know-how to move to viable volume production. Only Planar Systems, Greyhawk Systems, Hamlin-Standish, and Plasmaco are producing displays in mid- or high-volume facilities. Coloray, Magnascreen, Nitor, Projectavision, Tektronix, and Amtel Video are still working on prototypes and manufacturing questions. The rest have produced in low volumes for customers with specialized needs, primarily contractors of the Department of Defense.

IBM's effort is primarily in a joint venture with Toshiba, already mentioned in the section on Japan. Although there have been rumors about IBM's desire to establish an AM-LCD production facility in the United States, these rumors do not seem to be well founded.[30] Xerox is working on applying new polysilicon fabrication technologies to high-volume production, both in its Japanese subsidiary, Fuji-Xerox, and in an American joint venture with Hamlin-Standish. Texas Instruments is developing a display based on "deformable

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[30] See Corcoran [1991, pp. 112–114]. Several well-placed sources at IBM have flatly maintained to us that IBM is not establishing such facilities in the United States. Nor, given its current problems, would we expect IBM to do so in the future.

mirrors." Hughes is attempting to use its light-valve technology, developed for military applications, in commercial video projectors.

NCR, now a subsidiary of AT&T, is planning to invest in a plant to produce AM-LCDs in volume, possible in conjunction with some other firms. Motorola announced a decision late in 1992 to invest in a plant to produce super-twist LCDs that are actively addressed, which will permit the displays to approach the speeds required for full-motion video. Both Motorola and Intel are seeing increasingly a demand for full-motion video capabilities for computers and workstations, and are hoping that this demand will translate into increased demand for high-speed microprocessors and driver chips.[31] None of the large firms is currently involved in even low-volume production of flat panels or projection displays in the United States. And major potential customers of all of them (except perhaps of IBM) doubt whether even these larger firms have the corporate commitment and technical skills required to move into volume production if their approaches prove viable [based on industry sources].

U.S. firms do have some important strengths from which it may be possible to build an advanced display industry. Planar Systems, for example, is the world market leader in monochrome EL displays. If it can develop EL color displays at reasonably low prices, then it might be able to compete with Sharp, its main competitor in Japan. A number of DARPA contractors are developing innovative approaches to manufacturing cold cathode displays, which, if successful, will produce more compact, bright, and energy-efficient displays than those made by AM-LCD producers. Photonics is keeping up with Matsushita and Thomson in inventing color plasma displays and has demonstrated a 19-inch model that can handle full-motion video. As mentioned before, Tektronix has come up with a method of using gas-plasma to actively address LCDs without using either transistors or diodes to switch the pixels. Greyhawk Systems has a patented system for X-Y laser addressing of LCDs, which can produce very high-resolution images for flat-panel or projection displays. Amtel Video has developed a unique approach to modulating white light for video projection. Nitor will have access to inexpensive red, green, and blue lasers from Spectra Physics. And Projectavision has figured out how to remove the pixel structure from LCD projectors. Each firm has something to add to solving the difficult technological problems of making advanced displays.

However, all U.S. firms, even the large ones, are quite vulnerable to competition from Japanese firms, which have a lot of experience with high-volume manufacturing, access to patient capital, strength in a broad range of display technologies, and the willingness and ability to predate to preserve their market positions. As the antidumping petition indicated, none of the smaller, innovative U.S. firms can match this competition in the absence of correctives to the U.S. business environment. Moveover, given the asymmetrically easy access major Japanese firms have to the domestic U.S. technology supply base, it is easy to envision Japanese firms acquiring or becoming predominant partners with any of the smaller firms whose technological innovativeness would threaten established Japanese market position. Indeed, several of the U.S. firms with innovative approaches, like Amtel, are already being funded by Japanese firms wishing to hedge the risks of their own development efforts.

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[31] Telephone conversations with David Mentley, Stanford Resources, Inc., February 9, 1993.

Table 6. U.S. firms which closed or sold flat panel operations.

Company	Type of FPD	Sold or Closed	Date
AT&T	plasma	closed	1986
Control Data	plasma	closed	1980
Crystal Vision	AM-LCD	closed	1984
Exxon (Kylex)	AM-LCD	sold	1983
General Electric	AM-LCD	sold	1989
Hewlett-Packard	LCD	closed	1980
Honeywell (Alphasil)	AM-LCD	closed	1988
GTE	EL	closed	1987
IBM	plasma	sold	1987
LC Systems	AM-LCD	closed	1988
NCR	plasma	closed	1984
Panelvision	AM-LCD	sold	1986
RCA	AM-LCD	sold	1987
Sigmatron Nova	EL	closed	1988
Texas Instruments	LCD	closed	1980
Texas Instruments	plasma	closed	1983

Source: Dave Mentley, Stanford Resources, Inc., as cited in OTA [1990, p. 71]; interview materials.

As a result of entrenched Japanese competition conjoined with the lack of domestic skills and resources, most U.S. systems firms have simply abandoned the advanced display industry. Table 6 lists the U.S. firms that either closed a flat-panel production facility or sold one prior to 1990. The list includes many large systems firms: AT&T, Control Data, Exxon, GE, GTE, Hewlett-Packard, IBM, NCR, and Texas Instruments. Individually, each of the involved firms provides apparently reasonable justifications for abandoning this market. Common justifications include, among others, the belief that advanced displays are not central to the strategy of the firm, calculation that capital requirements for world-class manufacturing are too large a proportion of the total capital investment of the firm, and simple fear of Japanese competition eliminating profitability. Most often, however, these firms are motivated by one or both of the following beliefs: (1) advanced displays can be purchased on the open market at reasonable prices without fear of delays or interruptions in supply—that is, that an open and accessible merchant supply architecture in displays will exist; and (2) the firm can cut for itself a defensible and reliable supply deal with a major Japanese supplier, even if other firms will be victimized [conclusions based on interviews].

These perceptions on the part of the managements of many major U.S. firms are individually legitimate. They smack, however, of similar justifications heard time and again in other industries, beginning with consumer electronics producers like GE and RCA, who became dependent on their Japanese competitors for similar, apparently justifiable reasons. We believe these justifications are shortsighted because they do not fully take into account the ambitions of Japanese firms to compete in a wide variety of markets for electronic systems and the historical record of Japanese competitive strategies in semiconductor and other supply-base markets. Moreover, even if their actions work for individual firms, as argued earlier, there is no guarantee that the domestic U.S. economy will retain the advanced display know-how and production activities necessary to assure domestic capabilities for defense and other needs in this critical area of rapid, cumulative technological advance.

In our view, then, systems firms in both the United States and Europe will grow increasingly dependent on the supply of high-value-added components from a small number of Japanese competitors. They will lose market share in products that share manufacturing know-how and scale economies with integrated display systems. Defense agencies in both regions will be unable to purchase inexpensive procurement costs for military electronic systems or greater dependence on Japanese vendors for components. Furthermore, U.S. and European electronics manufacturing, particularly in the areas of semiconductors and systems assembly equipment, will continue to erode.

AMERICAN RESPONSES: WHAT IS TO BE DONE?

American national security and international economic competitiveness have depended in the past—and will continue to depend in the future—on maintaining a leading position in advanced electronics. In our view, that will be an increasingly difficult task because of the shifting supply architecture of underlying components, materials, and machinery technologies—illustrated here by our analysis of the advanced, high-resolution display industry.

If the supply architecture shifts from relatively open to closed, from competitive to oligopolistic, from dispersed to concentrated, there will be two primary effects on the U.S. position in electronics. Technological production activities and the associated electronics know-how will move out of the United States, thereby eroding the competitive potential of the activities and know-how that remain in the domestic economy. Simultaneously, the relevant advanced production activities and know-how, increasingly concentrated abroad, will become much less accessible for U.S.-based industry. Both of these trends represent a loss in a technological zero-sum game. Foreign competitors would increasingly dictate the terms of access to advanced technologies, the speed with which U.S.-based producers can incorporate those technologies into advanced products, and the price U.S.-based producers pay for the privilege.

If the U.S. position in electronics erodes, the United States loses far more than a major source of jobs and wealth. America is ceding to competitors abroad a defining characteristic of its national economy in the 20th century: the ability to shape its own technological destiny. Reversing this potentially dire constraint will not be easy. Therefore, the United States should act now to ensure that the constraint never fully materializes. Here, we can at best suggest the outline of an appropriate response.[32] There are two components, an external focus aimed at maintaining an open and internationally accessible global supply base in electronics and other high technologies, and an inward effort aimed at maintaining leading-edge production activities and know-how within the borders of the domestic U.S. economy. We briefly examine each in turn.

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[32] However, we hope to develop this conclusion at length into a separate paper in the near future.

Ensuring Access Abroad

In our view, ensuring an open and accessible electronics supply architecture will require fundamental changes in the post-WWII U.S. approach to trade policy.[33] In principle, every economy wants access for its firms to markets, technology, and investment opportunities in partner economies. But many Asian economies, and especially Japan, also want considerable control over foreign behavior in their domestic markets. That control may come by government restriction, as in Korea, or, as in Japan, by sharp limits on the ability of outsiders to buy into existing groups or participate in market privileges. The desire for unrestricted access abroad while maintaining restrictions on foreign practices at home can only be maintained so long as Asia's trading partners tolerate the game.

This problem lies at the heart of the contemporary U.S.–Japan disputes over trade and investment. It is crucially important to emphasize that the disputes are not about the formal principle of freedom of access—which has been the focus of U.S. trade policy toward Japan for close to three decades. Rather, the disputes are about the impacts and meaning of domestic Japanese policies and business practices that are not transparent and that implicate desires for national and regional autonomy in development. For example, domestic Japanese policies to accelerate productivity by supporting technological innovation are difficult in practice—perhaps impossible—to distinguish from strategies to create market advantage. Policies to promote the domestic diffusion of technology easily emulate mechanisms that support domestic producers at the expense of imports. In technology industries characterized by scale and learning economies in which costs drop dramatically as volume increases, Japanese forward pricing strategies are indistinguishable in practice from dumping.[34]

Judging whether such domestic practices and policies are simply idiosyncratic or are illegal barriers to trade requires inquiry into intent and effect. Three decades of fruitless trade negotiations have revealed that the current U.S. approach to trade cannot adequately cope with either the inquiry or its effective resolution. It is time to move beyond the typical U.S. focus on transparent and fair processes, imposing legal constraints on administrative discretion, and eliminating practices that differ from U.S. norms. The past decade has shown that the only trade policy that works with Japan is a results-oriented policy—one that focuses on negotiating substantive outcomes that are precisely specified, like specific import market shares in particular industries or specific investment targets.[35] That such an approach works has been demonstrated at least in part by the Semiconductor Trade Agreement, the opening of foreign procurement by Nippon Telegraph and Telephone, the reservation of Japanese radio spectrum for Motorola products, and the granting of retail licenses to Toys R Us.

Resolving the access problem, then, will require a managed solution with at least two features. The United States needs: (1) to insist on strict reciprocal

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[33] This subsection is partly drawn from Borrus, Sandholz, and Zysman [1992].

[34] Forward pricing occurs when a firm prices below current costs in anticipation of generating sufficient demand to push actual production costs down below the price target. Dumping is selling below a fair market value.

[35] On this point, and for a coherent argument in favor of managed trade, see Tyson [1992].

access to regional markets, investment opportunities, and supply-base technologies; and (2) to create an explicit bargain over outcomes wherever foreign industrial behavior cannot be reconciled with U.S. norms. First, reciprocal access to markets, investment opportunities, and underlying technologies is the only possible policy in this area: when know-how and markets for new technology cluster regionally and progress is driven by scale and learning, whoever has the broadest access to all three regions will likely end up dominant. Or, to put it another way, if we have access to three thirds of the world's storehouse of technologies relevant to our industry and you have access only to two thirds, we are likely to win over time. Reciprocity of access permits as much openness as each regional economy can tolerate politically and forces compromises in domestic practices that impede access whenever domestic industries seek foreign market opportunities.

Second, however, where foreign practices violate these (or other agreed) norms of behavior, the U.S. should negotiate to eliminate the *impacts* of the disruptive foreign practices. For example, for a variety of reasons, access to investment opportunities in manufactures in Japan is very limited. By the end of the 1980s, foreign direct investment in manufacturing accounted for less than one percent of Japanese manufacturing sales, employment, and assets [Graham and Krugman, 1989]. The comparable figures for the U.S. and Germany were 7–10 percent and 13–18 percent, respectively. To deal with this problem of asymmetrical access, the U.S. and Japan should negotiate inward investment targets, modeled after the market access provisions of the semiconductor trade agreement. Similarly, in cases where access impediments have led to the threat of a dominant position in a significant supply-base technology, the resulting market shares of the advantaged industry might be limited by agreement. For example, an agreed rule of thumb might mandate that at least one third of local consumption must be produced (without regard to ownership) within the disadvantaged region (with full local value-added). Foreign direct investment would be the vehicle to adjust national market shares. This would bring significant local production back into the economy that had been disadvantaged by the restrictive practices of its trading partner, would still reward innovating industries, but would simultaneously help to harmonize foreign disruptive practices with U.S. norms of behavior.

Gaining such reciprocal concessions abroad will require further changes in U.S. practices. Consider that we would never have negotiated for arms control the way we currently negotiate for trade concessions—by adhering only to abstract principle and disarming in pursuit of it. Instead we engaged in a massive arms build-up and then reciprocally negotiated concessions. The same approach is likely to be the only effective approach in the current trade climate. Only by engaging in some systematic practices to create domestic advantage will we be sufficiently armed to reciprocally bargain away practices and policies abroad that disrupt the functioning of an open world economy. Indeed, it was precisely the mutual concession of reciprocally lowering tariff barriers that drove the success of the first six rounds of tariff reduction in the Multilateral Trade Negotiations (MTN) under GATT auspices through the 1960s. In the 1970s and 1980s, the MTN floundered as interventionist practices accelerated abroad, only because the U.S. had few such practices to concede in return for the concessions it wanted from others.

Redevelopment at Home

Managed external access will thus prove ineffective—indeed, may not even be achievable—without continuing strength backed by activist policies at home. There is a surprising amount of agreement among analysts of all political persuasions as to what needs to be done at home. The normal catalogue includes: stable fiscal and monetary policies; encouraging productive investment and savings over consumption; favoring long-term financial holdings over short-term financial holdings over short-term financial transactions; and massive reinvestment in infrastructure and education.[36] Slightly more controversial, but endorsed here, are targeted policies to (1) assure cutting-edge development of technology and best industrial practices at home; (2) develop the mechanisms for the diffusion of advanced technology and practices throughout domestic industry; and (3) provide a capacity to absorb technology and best practices developed abroad.

We can effectively ensure that leading-edge technologies and know-how reside in the United States in only two ways—by redeveloping what has been lost or by repatriating what has gone abroad. Several existing U.S. policies, from those aimed at aggressive technology development at DARPA and NIST to regaining chip leadership via Sematech, aim at redevelopment of the capabilities of *U.S.-owned* enterprise. That route is necessary, if merely to keep *foreign-owned* suppliers honest in the market. It is, however, an extremely expensive route for an economy burdened with severe budgetary constraints and debt. There is also no guarantee that U.S. firms can acquire in a reasonable time frame the relevant know-how that has been developed abroad through decades of continuous reinvestment and learning. As a result, the United States also needs to think about ways of repatriating into the domestic economy foreign technologies and best practices.

This will likely require carefully targeted policies toward foreign direct investment that encourage foreign producers to transplant the full gamut of their most advanced activities into the United States. So long as the activities are resident in the U.S. economy and the domestic markets are open and competitive, foreign-ownership ought not to matter. This is a strategy that has been pursued effectively by other countries in similar situations in other industries—notably by the Europeans in the automobile industry from the 1950s on.

Conversely, the worst possible policy would be to deny the domestic economy foreign know-how that would otherwise benefit domestic growth and enhance productivity. Yet that is precisely the impact of current U.S. policy. Consider the characteristic remedy that was granted domestic flat-panel display producers in their dumping suit against Japanese display firms: an antidumping tariff on the display component.

Antidumping tariffs raise the price of the display component to U.S. electronic systems firms that produce products incorporating it. The tariff remedy disadvantages U.S. notebook firms, for example, since the tariff mandates that they pay more than their foreign competitors for the display component and charge higher prices in the market (or forego higher profits). Since imported notebooks are not subject to the same tariff on the embedded display component, U.S. firms ultimately lose market position. Similarly, the remedy buys

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[36] For details see, among many other sources, Cohen and Zysman [1987], Dertouzos et al. [1989].

at best a modest amount of time for the struggling U.S. display firms that brought the suit, but it does not even begin to address their real, fundamental needs for substantial investment capital and the know-how to enter high-volume manufacturing.

Worse still, by tariffing only the display component rather than embedded displays—that is, by failing to impose comparable tariffs on imported notebooks containing the display component—the remedy actually creates an incentive for U.S. notebook producers to move production activities offshore. They can avoid the tariff by importing the entire notebook computer from offshore affiliates or subcontractors, rather than by just importing the display component. The U.S. economy is the ultimate loser; when domestic producers like display firms and notebook computer manufacturers lose market position, the domestic economy eventually loses production operations and comes to rely on advanced activities and know-how that reside abroad.

What if the remedy had been to negotiate with the Japanese defendants to bring advanced display know-how and production into the United States via foreign direct investment from some of the Japanese firms like Sharp or Toshiba? U.S. notebook producers would have benefitted from increased local supply without increased component prices (since the tariff would have been avoided). The domestic economy would have benefitted by gaining new productive investment, manufacturing activities, and technological know-how. Even the domestic display manufacturers, who stand the most to lose under this scenario, could have been adequately compensated. U.S. display firms could have benefitted by acquiring know-how and investment capital if the negotiated form of foreign direct investment was volume production joint ventures in which those display firms were guaranteed some control and participation.

While undoubtedly controversial, this kind of policy is illustrative of what the United States needs to do to ensure a measure of autonomy and control over its own technological destiny. The shifting supply architecture (and the asymmetrical access to technologies it portends) is already altering the terms of competition in advanced electronics. In our view, doing nothing or simply muddling along will hasten the day when America's technological future is controlled largely from abroad. Despite its conservative appearance, doing nothing is in fact the most radical alternative because it risks the greatest loss of autonomy. The apparently more radical alternative of taking aggressive steps to safeguard the future is really the conservative thing to do, for it ensures that Americans will continue to control their own destiny.

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